Effects of lower extremity power training on gait biomechanics in old adults

Beijersbergen, Chantal

Chapter 4

Kinematic mechanisms of how power training improves healthy old adults' gait velocity

Chantal Beijersbergen
Urs Granacher
Martijn Gäbler
Paul DeVita
Tibor Hortobágyi

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Abstract

Introduction: Slow gait predicts many adverse clinical outcomes in old adults, but the mechanisms of how power training can minimize the age-related loss of gait velocity is unclear. We examined the effects of 10 wk of lower extremity power training and detraining on healthy old adults' lower extremity muscle power and gait kinematics. Methods: As part of the Potsdam Gait Study, participants started with 10 wk of power training followed by 10 wk of detraining (n = 16), and participants started with a 10-wk control period followed by 10 wk of power training (n = 16). We measured gait kinematics (stride characteristic and joint kinematics) and isokinetic power of the ankle plantarflexor (20°/s, 40°/s, and 60°/s) and knee extensor and flexor (60°/s, 120°/s, and 180°/s) muscles at weeks 0, 10, and 20. Results: Power training improved isokinetic muscle power by ~30% ($P \leq 0.001$) and fast (5.9%, $P < 0.05$) but not habitual gait velocity. Ankle plantarflexor velocity measured during gait at fast pace decreased by 7.9% ($P < 0.05$). The changes in isokinetic muscle power and joint kinematics did not correlate with increases in fast gait velocity. The mechanisms that increased fast gait velocity involved higher cadence ($R = 0.86$, $P \leq 0.001$) rather than longer strides ($R = 0.49$, $P = 0.066$). Detraining did not reverse the training-induced increases in muscle power and fast gait velocity. Conclusion: Because increases in muscle power and modifications in joint kinematics did not correlate with increases in fast gait velocity, kinematic mechanisms seem to play a minor role in improving healthy old adults' fast gait velocity after power training.

4.1. INTRODUCTION

Healthy aging modifies human gait, marked primarily by a slowing of gait velocity, a gross measure of ambulatory performance. Gait velocity is a strong biomarker for an array of medical, cognitive, and motor functions in old age. Indeed, longitudinal studies show that gait velocity measured at habitual and fast pace can independently predict disability [1], cognitive impairments [2], and even mortality [3]. Together with an increasing life expectancy, the maintenance of gait velocity has become a research and health care priority.

Modifications in stride characteristics and joint kinematics contribute to the age-related declines in gait velocity in old age. Compared with young adults, healthy old adults walk with shorter steps [4], and although freely chosen cadence changes little with age [5], when both walk at the same speed, elderly tend to walk with a higher cadence to compensate for the shorter steps [6,7]. Joint range of motion (ROM) at the ankle, knee, and hip joints are all reduced in old compared with young adults [4,8,9], but when measured at the same gait velocity, old adults walk with greater hip ROM [6,7,10].

Muscle power is the product of contractile force and velocity, and longitudinal studies show that muscle power compared to muscle strength declines earlier and more rapidly with age [11]. Lower extremity muscle power compared with muscle strength is a stronger physiological predictor of functional performance in old age [12,13] and correlates more strongly with lower intensity tasks such as walking compared with higher intensity tasks such as stair climbing [12]. In addition to the ability to generate contractile force, contractile velocity is also an important component of functional ability, and power training protocols focus on improving both contractile force and velocity by using moderately heavy weights (i.e., 60% of one-repetition maximum [1RM]) with the intention to move the weights as fast as possible during the concentric phase. In addition, lower extremity power training increases muscle power [14–16] and physical function in old adults [14,17], and previous research identified lower extremity muscle power as an important intervention target with the explicit goal to prevent and treat mobility disabilities in old age [13].

The most obvious mechanism through which power training improves gait velocity is that the old adults use the increased power and modify their joint kinematics (i.e., larger joint ROM and rotational velocities) that ultimately result in longer and faster strides. Curiously, to date there are no studies that examined how power training modifies stride characteristics and joint kinematics that underlie the training-induced increases in gait velocity. We previously found no association ($R^2 = 0.00$) between training-induced gains in lower extremity power (35%) and concomitant increases in gait velocity (13%) based on data pooled from eight studies [18].

Nevertheless, a few studies examined the effects of exercise interventions other than power training on gait velocity and kinematics [19–21] and provided limited and inconsistent insights into the biomechanical mechanisms of training-induced increases in gait velocity. To illustrate, 12 wk of lower extremity strength training increased gait velocity (12%), stride length (13%), cadence (10%), peak hip extension (85%),

knee extension (11%), and plantarflexion (25%) angles during stance [21]. However, strength improvements only moderately correlated with cadence and stride length (R^2 = 0.07–0.44), and the authors did not correlate changes in joint kinematics with changes in gait velocity. Other studies showed that yoga [20] or "combined exercise" [19] interventions failed to improve gait velocity but modified stride characteristics and joint kinematics. Overall, it is unclear how changes in lower extremity joint kinematics underlie intervention-induced and especially power training-induced increases in gait velocity. In addition, it is unresolved whether the withdrawal of the exercise stimulus in the form of detraining would causally weaken the relationships brought about by exercise intervention.

Thus, the aim of the present study was to determine the effects of lower extremity power training and detraining on lower limb muscle power and gait kinematics in community-dwelling old adults. We hypothesized that lower extremity power training improves muscle power, which in turn increases the magnitude and rate of joint ranges of motion in the three lower extremity joints during gait, resulting in larger steps, higher cadence, and ultimately higher gait velocity. We expected that increases in ankle, knee, and hip joint ROM and velocity would correlate with increases in gait velocity and that detraining would weaken these correlations, providing insights into the mechanisms of adaptations.

4.2. METHODS

4.2.1. Study design and participants

Data are from participants enrolled in the Potsdam Gait Study (POGS), and the study design, sample size calculation, and data collection methods have been detailed previously in the form of a study protocol [22]. In short, a group of 47 community-dwelling old adults age 65 yr and older applied for the study and were screened through a telephone and then in a face-to-face interview. Fifteen elderly did not qualify based on the exclusion criteria (for details, see Beijersbergen et al. [22]), and 32 elderly provided written consent to participate in the study. Sixteen participants started with 10 wk of lower extremity power training followed by 10 wk of detraining. Sixteen participants started with a 10-wk control period followed by 10 wk of lower extremity power training (Fig. 4.1). The ethics committee of the University of Potsdam, Germany, approved the study protocol (reference number 40/2014) that was conducted according to the ethical standards of the Helsinki Declaration.

4.2.2. Procedures

The Mini-Mental State Examination [23], the Short Physical Performance Battery [24], and the Freiburg Questionnaire of Physical Activity [25] were used to characterize the cognitive state, mobility disability, and health-related physical activity after enrollment. The participants performed the entire test battery at weeks 0, 10, and 20.

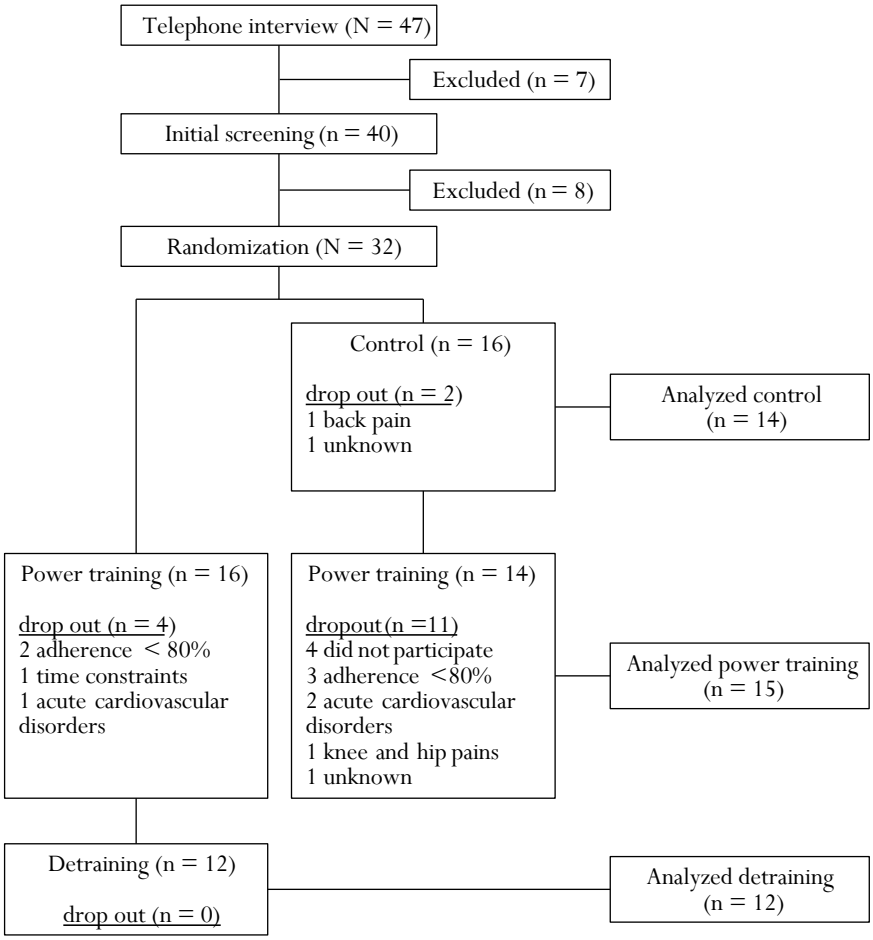

Figure 4.1. Flowchart of POGS.

4.2.3. Lower extremity power training

The training program consisted of 30 sessions administered for 10 wk (three per week) and focused on improving lower extremity muscle power [22]. Each session started with 3–5 min of warm-up, followed by leg press, ankle press, knee extension, and knee flexion exercises. Participants exercised using bilateral movements and performed three sets of 6–10 repetitions at 40%–60% of the 3RM for each exercise. We instructed the participants to move the weights rapidly and explosively during the concentric phase and return to the starting position after each repetition at a normal pace. Exercise progression was based on 3RM measured biweekly. For a participant's data to be included in the analyses, the minimum number of training was 24 of 30 sessions or 80% adherence. We instructed participants to maintain their pre-intervention habitual levels of activity during the control and detraining intervention.

4.2.4. Isokinetic muscle power tests

The maximal isokinetic power of the right ankle plantarflexors, knee extensors, and knee flexors was measured using an isokinetic dynamometer (Isomed 2000®, Hemau, Germany) [22]. Isokinetic ankle testing was performed at 20°/s, 40°/s, and 60°/s, and isokinetic knee testing was performed at 60°/s, 120°/s, and 180°/s. We calculated maximal muscle power (W) as the product of peak torque and angular velocity at peak torque.

4.2.5. Functional performance tests

We quantified functional lower extremity power by having participants climb two times one flight of 12 stairs, each with a height of 16.5 cm. Participants ascended and descended as fast and safely as possible, each task timed separately to the nearest 0.01 s. We used the fastest trial for each condition in the analysis. Stair climb power (W) was calculated as (body mass x gravitational acceleration) x (vertical stair height / time) and then normalized for body mass ($W \cdot kg^{-1}$). In addition, we characterized walking endurance using the 6-min walk test [26] by instructing participants to walk at their normal pace for 6 min.

4.2.6. Gait analysis

Gait analysis was conducted on a 4.2 x 1.5-m level walkway, and participants walked at a habitual, fast, and standardized speed of 1.25 m/s. Eighteen reflective markers were affixed on the right foot, shank, thigh, and pelvis, and we captured 3D marker kinematics at 100 Hz using nine infrared cameras (Vicon, Denver, CO). We collected five trials per walking condition, 15 trials in total per participant. Kinematic data were filtered with a fourth-order low-pass Butterworth filter at 6 Hz. We computed joint angular positions and velocities during one stride in 3D using Visual 3D software (C-Motion Inc., Rockville, MD). We analyzed stride characteristics and joint kinematics (i.e., peak joint angles, ROM, and peak joint angular velocities) and used the average of five trials per walking speed condition for each participant for the statistical analysis. The standardized walking condition allowed us to determine adaptations in gait kinematics that occur independent of changes in gait velocity.

4.2.7. Statistical analyses

This study was originally a crossover design, but because of a high dropout rate ($n = 17$, see Fig. 4.1 and Results for details), not every participant crossed over, and therefore we were forced to modify the originally planned statistical analyses [22]. In particular, instead of repeated-measures ANOVA, we compared before and after data for each intervention (power training, detraining, and control) using paired t-tests. The Shapiro–Wilk test confirmed the normality of the data. For the primary outcome measures of isokinetic muscle power and gait velocity, statistical significance level was set at $P < 0.05$. For the secondary outcome measures of stride characteristics (four variables per

Table 4.1. Participant characteristics at the start of each intervention.

	Power training	Detraining	Control
n (Male,Female)	15 (6,9)	12 (5,7)	14 (5,9)
Age, yrs	72.9 (5.4)	72.7 (5.2)	69.1 (4.4)
Height, m	1.67 (0.10)	1.67 (0.10)	1.68 (0.08)
Mass, kg	73.6 (14.6)	73.7 (15.4)	73.9 (11.4)
BMI, kg/m2	25.8 (3.9)	26.0 (3.9)	25.5 (3.2)
MMSE, score	29.1 (0.7)	29.3 (0.6)	28.9 (1.2)
FQoPA, hours/week	7.5 (5.0)	8.8 (4.7)	6.9 (5.1)
Maximal muscle power, W			
Knee extension 60°/s	97.5 (37.7)	117.3 (40.1)	98.4 (39.4)
Knee extension 120°/s	161.7 (64.5)	196.1 (70.6)	169.4 (61.7)
Knee extension 180°/s	216.9 (93.5)	254.3 (93.8)	229.2 (77.6)
Knee flexion 60°/s	54.6 (27.7)	72.7 (35.4)	54.6 (24.6)
Knee flexion 120°/s	104.6 (59.0)	125.3 (67.0)	103.4 (38.9)
Knee flexion 180°/s	167.7 (92.2)	181.5 (94.3)	156.6 (59.0)
Plantarflexion 20°/s	12.6 (8.1)	17.2 (9.4)	13.6 (6.7)
Plantarflexion 40°/s	23.3 (13.6)	29.4 (14.5)	25.3 (11.2)
Plantarflexion 60°/s	32.4 (21.1)	39.5 (19.8)	35.8 (15.8)
Physical performance			
SPPB, score	10.7 (1.1)	10.5 (1.1)	10.4 (1.3)
Stair ascent power, W/kg	4.05 (0.84)	4.30 (0.81)	4.26 (4.94)
Stair descent power, W/kg	4.48 (0.87)	4.86 (1.17)	0.67 (0.90)
Six-minute walk test, m/s	1.29 (0.14)	1.32 (0.13)	1.26 (0.14)
Habitual gait velocity, m/s	1.32 (0.16)	1.37 (0.13)	1.34 (0.15)
Fast gait velocity, m/s	1.85 (0.28)	1.91 (0.22)	1.98 (0.34)

Values are mean (±SD). BMI = Body Mass Index, MMSE = Mini Mental State Examination, FQoPA = Freiberg Questionnaire of Physical Activity, SPPB = Short Physical Performance Battery

walking speed condition) and joint kinematics (four variables per joint per walking speed condition), we applied a Bonferroni correction, and the level of significance was set at $P < 0.0125$ (0.05/4). We denote tendencies toward significance as $0.051 \leq P < 0.1$.

Within-group effect sizes (d) were calculated using z-scores for Cohen's d to ascertain if an effect was practically meaningful [27]. According to Cohen, effect sizes can be classified as small ($0.00 \leq d \leq 0.49$), medium ($0.50 \leq d \leq 0.79$), and large ($d \geq 0.80$) [27]. We additionally computed percent changes and presented values in the Results, unless otherwise stated, as mean and SD.

We used simple linear regression analysis to predict changes in gait velocity from changes in 3RMloads, isokinetic muscle power, stride characteristics, and joint kinematics. We quantified the associations between pairs of variables and between changes in variables as correlation coefficient (r value), level of significance (P value), and amount of variance explained (R^2 value). Values of $R = 0.10$ indicate small, $R = 0.30$ medium, and $R = 0.50$ large size of correlation [27]. We set the level of significance at $P < 0.05$ for the linear regression analysis, and we analyzed all data using the Statistical Package for the Social Sciences version 23.0 (SPSS Inc., Chicago, IL).

4.3. RESULTS

4.3.1. Participants

Two participants dropped out during the control period, and 15 participants dropped out during the power training due to illness, family reasons, and injuries not related to the training program (Fig. 4.1). We used 14 participants for the analysis of the control period, 15 participants for the analysis of the power training, and 12 participants for the analysis of the detraining (Fig. 4.1). Table 4.1 shows the characteristics of participants who started the power training, detraining, and control interventions.

4.3.2. Training progression

Lower extremity power training improved 3RM loads for all exercises, ranging from 39% for leg press to 63% for knee extension ($P \leq 0.001$, see Fig. B.1 in Appendix B). These finding are confirmed with the medium effect size for knee flexion ($d = 0.56$) and large effect sizes for all other exercises ($d \geq 1.04$).

4.3.3. Isokinetic muscle power

Table 4.2 shows the changes in isokinetic ankle and knee muscle power. Power training improved muscle power in all muscle groups and at all contraction speeds (range = 13%–48%, $P \leq 0.002$). Detraining and the control period did not affect isokinetic ankle and knee muscle power ($P > 0.05$), affirmed by the small effect sizes ($d \leq 0.34$).

4.3.4. Functional performance

Table 4.2 shows the changes in functional lower extremity power during stair ascent and descent and the changes in walking endurance during the 6-min walk test. Functional lower extremity power as measured with the stair ascent and descent test increased non-significantly by 9.7% ± 22.0% and 9.8% ± 23.1% after power training ($d \leq 0.46$) and then further increased by 12.4% ± 13.1% ($d = 0.63$) and 14.3% ± 14.2% ($d = 0.55$) after detraining ($P < 0.05$). Gait velocity during the 6-min walk test remained unchanged after power training, detraining, and control ($P > 0.05$, $d \leq 0.18$).

4.3.5. Training and detraining effects on gait velocity and stride characteristics

The analysis on the control period showed low reliability in only 1 of 51 dependent variables, providing a sound basis to detect reliable changes in stride characteristics and joint kinematics after power training and detraining that are not due to marker placement errors or test familiarization (see Table 4.3 and Table B.1 in Appendix B).

Table 4.3 shows changes in gait velocity and stride characteristics measured during habitual, fast, and standardized gait tests. Habitual gait velocity changed non-significantly by 3.2% ± 12.2% and -3.8% ± 9.0% after power training and detraining, respectively. Fast gait velocity increased by 5.9% ± 9.0% ($P < 0.05$) and tended to even further increase by 5.1% ± 8.1% ($P = 0.052$) after detraining. As expected, the

Table 4.2. Maximal muscle power and functional performance.

	Power training (n = 15)					Detraining (n = 12)					Control (n = 14)				
	Pre	**Post**	**%Δ**	**d**	**P**	**Pre**	**Post**	**%Δ**	**d**	**P**	**Pre**	**Post**	**%Δ**	**d**	**P**
Maximal muscle power, W															
Knee extension 60°/s	97.5 (37.7)	119.9 (43.2)	25.7	0.59	**≤0.001**	117.3 (40.1)	123.6 (35.2)	7.2	0.16	0.099	98.4 (39.4)	93.6 (39.1)	7.7	-0.12	0.680
Knee extension 120°/s	161.7 (64.5)	199.1 (72.8)	27.0	0.58	**≤0.001**	196.1 (70.6)	199.5 (61.0)	3.5	0.05	0.576	169.4 (61.7)	164.7 (49.2)	6.1	-0.08	0.738
Knee extension 1800°/s	216.9 (93.5)	256.9 (96.3)	23.2	0.43	**≤0.001**	254.3 (93.8)	260.9 (75.2)	4.8	0.07	0.534	229.2 (77.6)	234 (64.9)	7.1	0.06	0.685
Knee flexion 60°/s	54.6 (27.7)	71.5 (37.5)	30.6	0.61	**≤0.001**	72.7 (35.4)	71.1 (28.3)	0.8	-0.04	0.662	54.6 (24.6)	51.1 (20.4)	3.9	-0.14	0.557
Knee flexion 120°/s	104.6 (59.0)	126.8 (71.1)	22.2	0.38	**≤0.001**	125.3 (67.0)	128.9 (61.3)	5.1	0.05	0.569	103.4 (38.9)	101 (35.5)	3.7	-0.06	0.794
Knee flexion 180°/s	167.7 (92.2)	186.3 (96.9)	13.0	0.20	**0.002**	181.5 (94.3)	191.1 (91.8)	7.0	0.10	0.509	156.6 (59.0)	161.7 (50.3)	7.5	0.09	0.541
Plantarflexion 20°/s	12.6 (8.1)	17.3 (9.8)	48.4	0.57	**0.001**	17.2 (9.4)	18.9 (11.0)	10.6	0.18	0.334	13.6 (6.7)	15.3 (6.9)	19.2	0.25	0.095
Plantarflexion 40°/s	23.3 (13.6)	30.1 (16.0)	39.9	0.50	**≤0.001**	29.4 (14.5)	33.2 (19.3)	11.7	0.26	0.278	25.3 (11.2)	29.1 (14.7)	19.2	0.34	0.225
Plantarflexion 60°/s	32.4 (21.1)	40.8 (23.2)	41.9	0.40	**≤0.001**	39.5 (19.8)	45.6 (25.7)	15.3	0.31	0.209	35.8 (15.8)	36.6 (19.6)	1.0	0.05	0.734
Physical performanc															
Stair ascent power, W/kg	4.05 (0.84)	4.36 (0.92)	9.7	0.38	0.075	4.30 (0.81)	4.81 (1.00)	12.4	0.63	**0.006**	4.36 (0.65)	4.41 (0.85)	1.6	0.07	0.819
Stair ascent power, W/kg	4.48 (0.87)	4.88 (1.21)	9.8	0.46	0.061	4.86 (1.17)	5.51 (1.33)	14.3	0.55	**0.011**	5.01 (0.91)	5.21 (1.18)	3.7	0.22	0.225
Six-min walk test, m/s	1.29 (0.14)	1.31 (0.15)	1.6	0.18	0.252	1.31 (0.15)	1.34 (0.15)	1.3	0.14	0.410	1.26 (0.14)	1.27 (0.14)	0.8	0.03	0.293

Values are mean (±SD). d = within-group effect sizes, $\overline{\%\Delta}$ = mean percent change, P values are based on paired t-tests and significant P values are denoted in bold.

Table 4.3. Stride characteristics measured while walking at a habitual, fast, and standardized (1.25 m/s) speed.

	Power training (n = 15)					Detraining (n = 12)					Control (n = 14)				
	Pre	Post	%Δ	d	P	Pre	Post	%Δ	d	P	Pre	Post	%Δ	d	P
Habitual walking															
Velocity, m/s	1.32(0.16)	1.36(0.15)	3.2	0.25	0.220	1.37(0.13)	1.32(0.21)	-3.8	-0.38	0.216	1.35(0.14)	1.34(0.16)	-0.9	-0.07	0.652
Swing time, s	0.41(0.03)	0.40(0.03)	-0.7	-0.13	1.000	0.40(0.03)	0.40(0.03)	2.0	0.21	1.000	0.41(0.03)	0.41(0.03)	0.2	0.01	1.000
Stance time, s	0.64(0.05)	0.64(0.06)	-0.3	-0.08	1.000	0.62(0.05)	0.64(0.05)	3.1	0.34	0.677	0.67(0.06)	0.67(0.06)	0.8	0.07	1.000
Cadence, step/min	115.3(9.0)	116.3(9.3)	1.2	0.11	1.000	118.5(8.8)	115.6(7.8)	-2.2	-0.33	0.808	112.3(9.2)	111.8(8.8)	-0.4	-0.05	1.000
Stride length, m	1.38(0.17)	1.41(0.18)	2.1	0.18	0.448	1.40(0.17)	1.38(0.19)	-1.5	-0.12	1.000	1.44(0.13)	1.43(0.15)	-0.3	-0.08	1.000
Fast walking															
Velocity, m/s	1.85(0.28)	1.96(0.38)	5.9	0.39	**0.026**	1.91(0.22)	2.00(0.25)	5.1	0.41	0.052	1.97(0.35)	1.93(0.31)	-1.1	-0.18	0.526
Swing time, s	0.35(0.03)	0.35(0.03)	-1.6	-0.22	0.454	0.35(0.02)	0.34(0.02)	-2.8	-0.49	0.474	0.35(0.02)	0.35(0.04)	-0.4	-0.05	1.000
Stance time, s	0.51(0.05)	0.49(0.07)	-3.4	-0.32	0.367	0.49(0.04)	0.47(0.05)	-4.0	-0.52	0.322	0.52(0.06)	0.52(0.07)	1.1	0.07	1.000
Cadence, step/min	140.2(13.6)	144.7(17.2)	3.3	0.33	0.212	143.4(9.6)	149.2(13.8)	4.0	0.60	0.256	139.6(12.4)	138.8(16.6)	0.1	-0.06	1.000
Stride length, m	1.58(0.18)	1.62(0.18)	2.7	0.22	0.116	1.60(0.18)	1.61(0.17)	0.9	0.06	1.000	1.70(0.19)	1.66(0.19)	-1.0	-0.21	0.672
Standardized walking															
Velocity, m/s	1.24(0.05)	1.23(0.05)	-1.5	-0.25	0.217	1.24(0.02)	1.23(0.03)	-0.3	-0.50	0.685	1.25(0.03)	1.24(0.05)	-1.0	-0.67	0.313
Swing time, s	0.43(0.04)	0.42(0.04)	-2.2	-0.25	0.132	0.41(0.03)	0.42(0.03)	2.8	0.35	**0.036**	0.42(0.03)	0.42(0.04)	0.9	0.10	1.000
Stance time, s	0.67(0.07)	0.68(0.07)	1.6	0.15	0.314	0.67(0.06)	0.68(0.06)	2.6	0.26	0.438	0.69(0.06)	0.70(0.06)	0.7	0.08	1.000
Cadence, step/min	109.0(11.0)	109.1(10.5)	0.0	0.01	1.000	112.0(9.1)	109.1(8.4)	-2.4	-0.32	0.136	108.6(8.7)	107.7(7.8)	-0.7	-0.10	1.000
Stride length, m	1.39(0.15)	1.37(0.12)	-1.8	-0.13	0.760	1.34(0.10)	1.37(0.11)	2.8	0.30	0.180	1.39(0.10)	1.39(0.09)	0.0	0.00	1.000

Values are mean (±SD). d = within-group effect sizes, $\overline{\%\Delta}$ = mean percent change, P values are based on paired t-tests and, except for gait velocity, Bonferroni corrected. Significant P values are denoted in bold.

standardized gait velocity was nearly identical after power training and detraining ($P > 0.05$), but detraining increased swing time by 2.8% ± 3.1% ($P < 0.05$). The effect sizes for change in gait velocity and stride characteristics were small ($d \leq 0.42$) for power training and detraining, except for a medium effect on change in stance time ($d = -0.52$) and cadence ($d = 0.60$) during fast walking after detraining.

4.3.6. Training and detraining effects on joint kinematics

Table B.1 (Appendix B) summarizes the effects of training, detraining, and control period on joint kinematics measured during habitual, fast, and standardized walking. Measured during habitual walking, participants tended to contact the ground with 1.7° ± 2.8° ($P = 0.065$) less knee flexion after power training, and there was a medium effect ($d = 0.53$) for the 8.8% ± 23.8% decrease in knee extensor velocity during stance after detraining. Measured during walking at fast speed, plantarflexor velocity during push-off decreased by 7.9% ± 8.7% ($P < 0.05$), and ankle ROM tended to decrease by 2.0° ± 3.5° after power training ($P = 0.091$). Measured during walking at the standardized speed, there was a medium effect ($d = 0.65$) for the 4.6% ± 28.7% decrease in dorsiflexion position during stance after power training.

Changes in fast gait velocity did not correlate with changes in 3RM training loads, nor did it correlate with changes in isokinetic muscle power (Fig. B.2 in Appendix B). Figure 4.2 illustrates that the changes in fast gait velocity correlated with changes in cadence ($R = 0.86$, $P < 0.001$), ankle ROM ($R = 0.52$, $P = 0.048$), and tended to correlate with stride length ($R = 0.49$, $P = 0.066$). Changes in peak plantarflexor velocity during push-off did not correlate with changes in fast gait velocity ($R = 0.15$ $P > 0.05$).

4.4. DISCUSSION

A 10-wk lower extremity power training program improved plantarflexor, knee extensor, and knee flexor power and fast gait velocity but had no effects on healthy old adults' habitual gait velocity, stair climbing power, and walking endurance. Improvements in fast gait velocity correlated with an increase in cadence but not with training-induced improvements in lower extremity power or joint kinematics.

4.4.1. Training and detraining effects on muscle power

Resistance training interventions can substantially increase muscle power in old adults [15], but improvements in muscle power are greatest when power training protocols, similar to the one used in the present study, are used [14–16]. Our participants substantially increased muscle power by ~30% (Table 4.2), and these muscle power gains exceed the 17% gains in knee extensor and plantarflexor power reported previously in studies with similar training parameters in healthy old adults [28,29]. Ten weeks of detraining did not decrease muscle power, and this confirms previous findings, showing no decrease

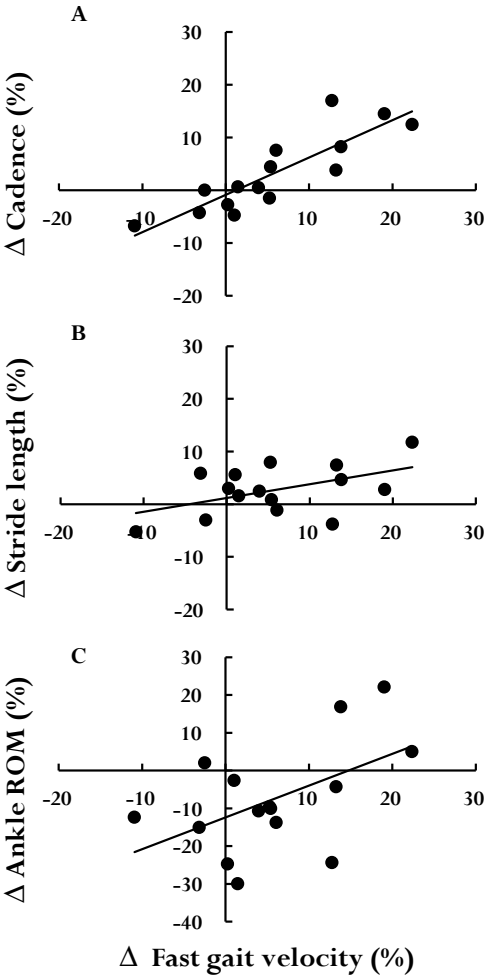

Figure 4.2. Associations between changes in stride characteristics or joint angular position and changes in fast gait velocity as a result of power training (n = 15). Panel A, Stride length and fast gait velocity: y = 0.26x + 1.16, R = 0.487, R^2 = 0.237, P = 0.066. Panel B, Cadence and fast gait velocity: y = 0.71x j 0.86, R = 0.864, R^2 = 0.746, P ≤ 0.001. Panel C, Ankle ROM and fast gait velocity: y = 0.84x j 12.39, R = 0.517, R^2 = 0.267, P = 0.048.

in leg extension strength after 3 wk of detraining in old adults [30] and a maintenance of muscle strength for 6 months by exercising only once per week [31]. Overall, power training is a successful method to increase healthy old adults' lower extremity muscle power, and the power gains can be maintained for at least 10 wk after withdrawing the exercise stimulus (detraining).

4.4.2. Training and detraining effects on gait velocity

Muscle power correlates with habitual gait velocity in old adults (R = 0.59) [12], and a recent meta-analysis showed that resistance training in general, not limited to power training, can increase healthy old adults' habitual gait velocity statistically and clinically meaningfully by 0.09m/s or 6.8% [32]. Interestingly, power training improved muscle power by ~30%, but habitual gait velocity measured during the 6-min walk test and the kinematical gait test remained unchanged. These findings are consistent with power training studies in high-functioning old adults showing that 8 wk of power training improved leg press strength by 25% (muscle power was not tested) but had no effects

on habitual gait velocity measured during a 6- and 400-m walk [33]. In addition, 12 wk of power training improved leg press power by 22%, but habitual gait velocity measured during eight feet remained unchanged (-1.5%) [34]. These data suggest that substantial improvements in muscle power do not always modify healthy old adults' personal preferences as to what they perceive as a habitual or comfortable gait velocity. Our participants' healthy and high-functioning status at baseline could be one potential reason for a lack of increase in habitual gait velocity. Indeed, the 1.32m/s habitual gait velocity at baseline compares well with the 1.31m/s reported earlier for healthy old adults 60–70 yr old [19] and even with young adults' habitual gait velocity [6]. Although habitual gait velocity was unchanged, the training-induced muscle power gains may be functionally important during rapid movements that require larger amounts of muscle power, such as avoiding a fall after a trip.

Lower extremity power training improved fast gait velocity by 0.11m/s (Table 4.3), which is nearly numerically identical with the 0.12m/s increase in healthy old adults after resistance training summarized in a meta-analysis [32]. Remarkably, our participants walked 0.39m/s faster at baseline compared with the velocity at baseline reported in the meta-analysis (1.85 vs 1.46m/s) [32] and still improved by a similar amount. Cross-sectional studies show that fast compared with habitual gait velocity declines earlier and more steeply with increasing age [35], and lower extremity muscle power is more strongly associated with fast ($R = 0.45$) compared with habitual ($R = 0.26$) gait velocity [36]. This suggests that gait velocity measured at fast rather than at habitual pace may be particularly sensitive to power training, especially in healthy, well-functioning, old adults.

An interesting finding was the maintenance of muscle power and the strong tendency for a further improvement in fast gait velocity after 10 wk of detraining. Such changes with detraining suggest that both physiological and functional performance can remain elevated for at least 10 wk after withdrawing the exercise stimulus.

An important aim of the present study was to determine how, if at all, the training-induced improvements in lower extremity muscle power would translate to improved gait velocity. We found that the improvement in ankle plantarflexor, knee extensor, and knee flexor power did not correlate with increases in fast gait velocity ($R = 0.09–0.42$, $P > 0.05$, see Fig. B.2). This is in line with a systematic review that found zero association between gains in training-induced lower extremity muscle power (35%) and the concomitant increases in gait velocity (13%) based on data pooled from eight studies [18]. However, when very frail old adults, who walked at 0.54m/s during a fast gait test at baseline, performed power training, changes in knee extension power and changes in the time to perform a 6-m walk did correlate albeit poorly ($R = -0.42$) [14]. Altogether, the data suggest that the effectiveness of power training in improving gait velocity depends on participants' functional status at baseline, whereby frail compared with healthy old adults would benefit more.

The absence of association between muscle power gains and increases in fast

gait velocity observed in the present study suggests that factors other than improved muscle power mediated the increases in gait velocity after power training. Such factors can include but are not limited to fitness-related increases in balance and coordination [37], neuromuscular adaptations [38], confidence, improved executive function [39], or self-efficacy [40]. Participants perceive that they possess improved physical abilities after the intervention but use only a fraction of the improved physical abilities to walk faster. This idea is further supported by the maintained lower extremity muscle power after detraining, together with a strong tendency toward even further improvements in fast gait velocity (Tables 4.2 and 4.3).

4.4.3. Training and detraining effects on joint kinematics

Old compared with young adults generally walk with smaller ankle joint ROM, mainly caused by reduced plantarflexion during push-off [6,7]. Resistance training can increase old adults' ankle ROM during gait [19,21] by increasing maximal plantarflexion position during push-off, providing indirect evidence for a better and more forceful push-off [19]. By contrast, the present study showed a 7.4% decrease in ankle ROM together with a 7.9% decrease in plantarflexor velocity during push-off during fast walking after power training. Such adaptations, rather unexpectedly, suggest a less powerful ankle push-off during gait and contrast sharply with the 43% increase in maximal plantarflexor power measured on the dynamometer and the 5.9% increase in fast gait velocity. Moreover, detraining resulted in maintenance of the plantarflexor power measured on the dynamometer (Table 4.2) and fast gait velocity (Table 4.3), yet ankle ROM during gait increased by 9.2% (Table B.1), suggesting a dissociation between ankle joint kinematics and maximal plantarflexor power. Taken together, ankle joint kinematics during gait behave independently and inconsistently in relation to the power training stimulus and its withdrawal, and it remains unclear whether it is necessary to improve old adults' maximal plantarflexor muscle power, ankle ROM during gait, or plantarflexor velocity during push-off for increasing gait velocity.

4.4.4. Correlations between changes in gait velocity and changes in gait kinematics

The present data did not bear out the hypothesized reciprocal strengthening and weakening of the relationships between muscle power, joint kinematics, and gait velocity after power training and detraining. Changes in cadence explained up to 75% of the changes in fast gait velocity compared with the 24% explained by changes in stride length (Fig. 4.2). This suggests that the increased ability to produce higher joint rotational velocities is more important than to produce larger joint amplitudes to increase gait velocity after power training. Cross-sectional studies further support this idea by showing that when old adults walk at faster velocities, they also walk with higher cadence but do not increase their stride length [6,7]. Nevertheless, the changes in individual joint velocities did not correlate with increases in gait velocity and the kinematic mechanisms

of how power training increases gait velocity remains unknown.

4.4.5. Limitations

First, participants in the present study were healthy and high-functioning old adults, and therefore the effectiveness of the power training to improve gait velocity and gait kinematics may have been limited. Because of our participants' high functionality, our results cannot be generalized to mobility impaired or frail old adults. Second, plantarflexor power was measured during isokinetic contractions at relatively slow speeds (20°/s–60°/s) compared with the ~300°/s ankle joint velocities present during gait, and the low testing speeds could have underestimated maximal plantarflexor power. Third, despite rigorous standardization, it is still possible that there were random errors in marker placements because it is not possible to place the markers exactly on the same position over anatomical landmarks. We suspect, however, that such errors were not systematic and did not bias the data because the kinematic variables were unchanged and thus reliable in the nonintervention control group.

4.5. CONCLUSION

A 10-wk lower extremity power training program increased healthy old adults' ankle and knee muscle power and fast but not habitual gait velocity. Gains in muscle power and fast gait velocity did not diminish after 10 wk of detraining. Because the increases in muscle power and modifications in joint kinematics did not correlate with increases in fast gait velocity, the kinematic mechanisms of how power training improves healthy old adults' gait velocity remains unclear. Future studies will determine the effects of lower extremity power training on joint kinetics, providing deeper insights into the biomechanical mechanisms of how lower extremity power training increases healthy old adults' gait velocity.

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